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ABSTRACT

For the first time a burst of suprathermal electrons is observed from the exploding laser-entrance-hole window of gas-filled hohlraums driven with 13.5 kJ of 351-nm laser light. The two-plasmon-decay instability appears to produce up to 20 J of hot electrons with $T_{\text{hot}} \sim 75$ keV at early times and has a sharp laser-intensity threshold between 0.3 and 0.5×10^{15} W/cm^2. The observed threshold can be exploited to mitigate preheat by window hot electrons in ignition hohlraums for the National Ignition Facility and achieve high-density, high-pressure conditions in indirect drive implosions.

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Energy gain with inertial confinement fusion (ICF) [1,2] is predicted to be achieved on the 192-beam, 351-nm, 1.8-MJ National Ignition Facility (NIF) [3]. It will be explored first with indirect-drive ICF, which uses an ignition target consisting of an implosion capsule placed in the center of a high-Z radiation cavity, called a hohlraum [2]. The NIF laser beams are arranged in two cones around the poles of the spherical target chamber to irradiate both sides of the cylindrical hohlraum through the laser entrance holes (LEH). The laser beams irradiate the inner high-Z wall (i.e., Au, U) of the hohlraum, and the resulting high-Z plasma radiates x rays that are trapped and re-radiated by the opaque hohlraum wall and uniformly ablate the implosion capsule [2,4]. Ignition requires high-compression implosions (i.e., the ratio of the initial capsule radius to the compressed capsule radius is ~30), which places strict requirements on the irradiation-nonuniformity level of the x-ray drive on the capsule (<1-2% rms) and on the compressibility of the DT fuel. The required drive symmetry is more likely to be achieved if the hohlraum is filled with a low-Z gas fill, which minimizes the motion of the laser-deposition region [2]. A thin (0.5 μm) polyimide window covering each LEH is required to initially contain the gas fill.

High compressibility requires that the DT fuel remain close to Fermi degenerate throughout the implosion [2]. This requires control of irreversible heating of the DT fuel, leading to precise pulse shaping to minimize shock heating of the fuel [2,5]. Any additional irreversible heating sources such as suprathermal or hot electrons (T_{hot} > 20 keV) produced by laser–plasma interactions need to be understood and controlled. Hohlraums are also used as a driver for high energy density physics, encompassing the research of plasmas having energy densities exceeding 10^{11} J/m^3, or equivalently, pressures greater than 1 Mbar [6-9]. The suppression of hot electrons in hohlraums is critically important for researchers seeking to achieve high compression, high pressure conditions in matter for planetary interior studies [7], phase transition, conductivity and equation of state measurements [8], and laboratory astrophysics experiments [9]. This Letter reports, for the first time, evidence of hot-electron production during the early-time burnthrough of the LEH window, which, if not properly controlled, could lead to unacceptably large hot-electron preheat of the DT fuel in an ignition capsule on NIF.

The possible sources of hot electrons are the two-plasmon-decay (TPD) instability [10,11] and stimulated Raman scattering (SRS) [11]. The TPD instability occurs near the quarter-critical density when the laser light decays into two electron-plasma waves or plasmons. An experimental signature of TPD instability is significant $3\omega/2$ emission, which is Thomson scattering of the laser drive with a frequency ω from the plasmons. SRS involves the decay of a laser photon into a plasmon and a scattered photon in the visible spectrum. Wave–particle interactions (e.g., Landau damping, trapping, and wave breaking) can generate hot electrons [11], and Coulomb scattering of the hot electrons in the high-Z wall of the hohlraum produces hard x-ray bremsstrahlung emission [12].

This Letter shows that gas-filled hohlraums driven with 13.5 kJ of 351-nm laser light on the OMEGA laser system [13] produce two bursts of hot electrons. The first burst is attributed to be from the TPD instability in the exploding LEH window, and produces, at OMEGA scale, up to 20 J of hot electrons with $T_{hot} \sim 75$ keV. It has a sharp laser-intensity threshold between 0.3 and 0.5×10^{15} W/cm^2. The TPD instability has been observed in direct-drive ICF [14]; however, this is the first observation of the TPD instability for indirect-drive ICF using 351-nm laser light. Previous experiments were not sensitive to window hot electrons [12,15,16], which are the main subject of this Letter. The second pulse of hot electrons with $T_{\text{hot}} \sim 20$ keV appears to be produced by SRS during the main laser drive and has been studied extensively [11,12,15].

The hard x-ray diagnostic (HXRD) has four high-pass energy channels recording time-resolved measurements along a line of sight 42° to the hohlraum axis with a 120-ps rise time and a $1/e$ decay time of 1.2 ns [17]. The number of Joules of hot electrons, E_{hot}, and the temperature characterizing the Maxwellian distribution of hot electrons T_{hot} were inferred from the HXRD measurements using the thick-target bremsstrahlung radiation approximation

$$\frac{\mathrm{d}I}{\mathrm{d}\nu \mathrm{d}\Omega} = \frac{5\times 10^{11}}{4\pi} E_{\text{hot}} \frac{Z}{79} \exp\left[1 - \frac{h\nu}{T_{\text{hot}}}\right] \text{keV/keV/sr} ,$$

where Z is the atomic number of the hohlraum wall material [12]. Attenuation of the lower-energy hard x rays by the Au hohlraum wall was included in the analysis. An *in-situ* intensity calibration was performed on the HXRD using the hard x-ray emission spectrum from a vacuum Au hohlraum irradiated with an 18-kJ, 1-ns square laser pulse. The calibration relied on earlier experiments on the NOVA laser: the hard x-ray emission from a vacuum Au hohlraum was measured [12], and a Maxwellian distribution of hot electrons with $T_{\text{hot}} = 30$ keV and $f_{\text{hot}} = 0.3\%$ to 1.0% was inferred [16], where f_{hot} is the fraction of laser energy E_{UV} converted to hot electrons (i.e., $E_{\text{hot}} = f_{\text{hot}}\, E_{\text{UV}}$). The laser drive and hohlraums of the OMEGA and NOVA experiments were similar, with the following exception: OMEGA had 40 drive beams smoothed with phase plates compared to 10 defocused drive beams on NOVA. The calibration of the HXRD on OMEGA used T_{hot} = 30 keV and f_{hot} = 1%; therefore, the estimates of E_{hot} reported in this Letter represent upper limits. The factor of three uncertainty in the absolute value of E_{hot} does not affect the scaling of hot electron production with the overlapped laser intensity on the window nor the inferred values of T_{hot}. The $3\omega/2$ emission from the LEH was recorded along a line of sight 45.3º from the hohlraum axis with a 100-ps temporal resolution and a 0.5-nm spectral resolution [18]. The SRS scattered directly back into the OMEGA lens of a cone 3 beam was recorded with a full-aperture backscatter station [18].

Each side of the gas-filled Au hohlraum was irradiated with 20 beams arranged in three cones, smoothed with phase plates, and having a laser bandwidth of less than 0.015 THz [19]. The single-beam focal spot was elliptical with the minor axis lying in the plane of incidence defined by the hohlraum axis and the beam axis [19]. The wall thickness, length, inside diameter, and LEH diameter of the hohlraum were 2 to 5 μm, 2.3 to 2.55 mm, 1.6 mm, and 1.07 to 1.2 mm, respectively. The cone 1 (5 beams/side), cone 2 (5 beams/side), and cone 3 (10 beams/side) beams had angles of incidence to the hohlraum axis of 21.4°, 42.0°, and 58.8°, respectively, and were fired simultaneously. Best focus of all the beams occurred at the LEH plane. The beams of cones 2 and 3 were pointed to the center of the LEH and contributed to the peak overlapped laser intensity. Cone 1 beams were aimed at a point on the hohlraum axis 600 μm outside of the LEH window and did not overlap the other beams at the LEH. All of the hohlraums had a 0.6-μm-thick polyimide window, which is close to the 0.5-μm LEH window thickness of the NIF target. The initial fully ionized electron density n_e of the hohlraum plasma was either 0.04 or 0.1 n_{cr}, where n_{cr} is the critical density given as $n_{cr} = 1.1 \times 10^{21}/\lambda_{\mu m}^2$ cm^{-3} = 9.0

$\times 10^{21}$ cm^{-3}. The 0.9 atm. gas fill for the higher (lower) n_e was C_5H_{12} (76% CH_4 + 24% C_5H_{12}). The critical density in a cryogenic NIF ignition hohlraum will be ~0.04 n_{cr}, but the fill gas will be a mixture of H and He instead of hydrocarbons [2].

The time history of hard x rays with hν > 40 keV (black line) recorded for a gas-filled Au hohlraum is compared with the shaped laser drive (red line) generated with a single-seed pulse in Fig. 1(a). The peak overlapped foot laser intensity of cones 2 and 3 at the LEH window was ~1.2 × 10^{15} W/cm^2 and n_e = 0.1 n_{cr}. The first burst of hard x rays occurs at t = 0.3 ns around the time of peak laser foot power, while the second burst of hard x rays occurs at t = 2.2 ns shortly after the time of peak laser power. The x-ray fluence of each hard x-ray pulse was calculated for each of the four energy channels, and T_{hot} and E_{hot} were quantified using a least-squares-fitting routine. The time-resolved $3\omega/2$ spectrum is shown in Fig. 1(b) and the time-resolved SRS in Fig. 1(c). Overplotted on the streaked spectra in Figs. 1(b) and 1(c) are the laser drive and the spectrally integrated scattered-light signals. The first x-ray pulse, broadened by the temporal response of HXRD, correlates with the $3\omega/2$ emission during the foot of the laser drive, and the second x-ray pulse correlates with the SRS during the main drive. When the intensity threshold for TPD (SRS) is not exceeded, neither the $3\omega/2$ (SRS) nor the HXRD signals are observed.

The peak overlapped laser intensity of cones 2 and 3 at the LEH during the foot of the laser drive was varied from 0.5 to 1.5 × 10^{15} W/cm^2. The overlapped intensity was controlled by either varying the number of beams irradiating the LEH window or by varying the single beam intensities of all the beams (E_{UV} for the first 0.5 ns varies from 350 to 800 J). The majority of the shots used all three beam cones (drive A); while one subset of the shots fired only the 58.8º cone 3 beams (drive B) and another subset fired only the 21.4º cone 1 and 42º cone 2 beams (drive C). The inferred values of E_{hot} for all the drives under consideration show a scaling with the overlapped intensity of the cone 3 beams at the LEH window. The results in Fig. 2(a) show a threshold for hot electron production when the cone 3 beam overlapped intensity is changed from 0.3 to 0.5 × 10^{15} W/cm^2. The circles and triangles represent $n_e = 0.04\ n_{cr}$ and $n_e = 0.1\ n_{cr}$, respectively. With the higher n_e and an overlapped LEH laser intensity of the cone 3 beams of ~0.7 × 10^{15} W/cm^2, E_{hot} is approximately 20 J. For the NIF-ignition-hohlraum-like density ($n_e = 0.04\ n_{cr}$) with the high overlapped intensity, E_{hot} is between 2 and 5 J. Inconsistencies were found when using the total overlapped intensity as a scaling parameter for the ensemble of drive A, drive B and drive C data. In particular, the drive B data (58.8º beams) lies well above the rest of the data when total overlapped intensity is used. This empirical finding may be due to the dielectric swelling factor, which is a plasma effect that increases the local intensity in the vicinity of a turning point. For the 58.8º beams, the turning point in the exploding window plasma will be near the quarter-critical density. Consequently, those beams are subject to a "TPD resonance" in which the intensity increase due to swelling coincides with the density at which the TPD instability is liable to occur.

The scaling of T_{hot} with the overlapped cone 3 intensity is shown in Fig. 2(b). The hohlraums with $n_e = 0.1\ n_{cr}$ and the highest overlapped intensity have $T_{hot} \sim 75$ keV. More scatter was observed for $n_e = 0.04\ n_{cr}$ at the highest overlapped intensities, with T_{hot} ranging from 40 keV to 80 keV. Most of the measurements with the lowest, below threshold, overlapped intensity show a decrease in T_{hot} to ~ 30 keV. The signals shown in Fig. 1 are well above the intensity threshold for the TPD instability, and have E_{hot} ~ 20 J and T_{hot} ~ 70 keV.

The linear theory of Simon for the TPD instability [10] predicts $T_{\text{hot}} \geq 70$ keV for the simulated electron temperature T_e in the exploding window of an OMEGA hohlraum, which is consistent with measurements during the early part of the laser pulse. According to the theory, the TPD instability occurs only in the vicinity of quarter-critical density, and the threshold intensity for the TPD instability, $I_{\text{thresh}} = 70.5\, T_e[keV] \Big/ \lambda[\mu m] L[\mu m] \times 10^{14} \dfrac{W}{cm^2}$, is a function of the laser wavelength λ, T_e and density gradient scale length in the direction of the laser beam, $L = n_e \left(\dfrac{\partial n_e}{\partial x}\right)^{-1} = \dfrac{n_{cr}}{4}\left(\dfrac{\partial n_e}{\partial x}\right)^{-1}$ [10]. Simon's theory was used to post-process the simulations of these experiments from the 2-D radiation hydrodynamics code HYDRA [20] to estimate an "energy at risk for generating window hot electrons," E_{risk}. This is the time integral of the laser power P_{pass} that passes the quarter-critical surface with intensity above the threshold. Characteristic values of T_e and L were extracted from the HYDRA simulation (T_e = 0.3-1.3 keV and L = 10-100 μm) to test if the threshold was exceeded. As the window explodes the density gradient scale length increases. The overlapped beam intensity of the cone 3 beams is used in the threshold formula (i.e., $I_{\text{overlap}} = 10\, I_{\text{single beam}} \cos(58.8°)$). The energy at risk of scattering into two plasmons is then given by

$$E_{\text{risk}} = \int_t P_{\text{pass}} H\left(P_{\text{pass}} - P_{\text{thresh}}\right) \mathrm{d}t = \int_t \mathrm{d}t \sum_N P_{\text{ray}} H\left(\frac{I_{\text{pass}} - I_{\text{thresh}}}{I_{\text{thresh}}}\right).$$

Here, H is the Heaviside function and P_{pass}–P_{thresh} is the laser power with intensity $I > I_{\text{thresh}}$ and P_{ray} is the power of each of the N computed laser rays as it crosses the quarter-critical surface. In HYDRA, the average intensity, defined as the amount of power traversing a zone, is used to represent the overlapped intensity I.

When the laser beams initially ablate the LEH window, they launch a shock wave. As the window plasma expands to low density, the laser-energy-deposition rate drops. The shock wave becomes unsupported and transits into the gas plasma behind the window as a hemispherical blast wave. When the blast wave expands below $n_e = 0.25\ n_{cr}$ everywhere, the risk of the TPD instability is gone. For hohlraums with an initial gas plasma density of $n_e = 0.04\ n_{cr}$, HYDRA simulations show that the blast-wave density is below $n_e = 0.25\ n_{cr}$ as soon as it enters the gas region. For the $n_e = 0.10\ n_{cr}$ hohlraums, the blast-wave peak density remains above $n_e = 0.25\ n_{cr}$ for about 0.1 ns after the blast wave enters the gas plasma. Post-processed HYDRA simulations predict that E_{risk} should drop by a factor of three between $n_e = 0.10\ n_{cr}$ and $n_e = 0.04\ n_{cr}$, which is consistent with the upper range of the points in Fig. 2(a). They also confirm that E_{risk} decreases with intensity; however, the predicted scaling is too slow to explain the rapid drop observed in E_{hot}. The observed drop is possibly due to a decrease in the efficiency of trapping and accelerating electrons in the plasmons, which is not modeled in Simon's theory [10].

HYDRA simulations show that the window burnthrough phase of the gas-filled OMEGA hohlraum is hydrodynamically similar to that of an ignition hohlraum. When extrapolating the OMEGA window hot electron data to a NIF ignition hohlraum, the inferred values of E_{hot} are multiplied by a factor of 10 to account for the increase in the LEH window area of the NIF target. Fig. 3 presents the E_{hot} - T_{hot} plane with the window hot electron data from OMEGA scaled up to a NIF target. The dotted line in Fig. 3 represents the early time allowable E_{hot} limit based on 2-D simulations of a NIF ignition target, which is dependent on T_{hot} (i.e., $E_{hot} \sim 1/T_{hot}^2$). Most of the data in Fig. 3 are above the NIF limit; however, points below the line meet the NIF requirement, with the most NIF-like point ($n_e = 0.04\ n_{cr}$ and cone 3 overlapped intensity of 0.3×10^{15} W/cm^2) being at least an order of magnitude below the NIF limit. As a result of this finding, the initial overlapped laser intensity incident on the LEH window of an ignition target for the NIF has been set to be 0.2×10^{15} W/cm^2, which is below the measured threshold intensity. Once the quarter-critical density disappears, the laser intensity is increased.

In conclusion, the TPD instability in the exploding LEH window of a gas-filled hohlraum appears to produce up to 20 J of hot electrons with $T_{\mathrm{hot}} \sim 75$ keV at early times and has a sharp laser-intensity threshold between 0.3 and 0.5×10^{15} W/cm^2. The observed threshold can be exploited to mitigate target preheat by window hot electrons in NIF ignition hohlraums and in low-entropy compression experiments. Simulations using a 2-D radiation hydrodynamics code and a linear theory of the TPD instability show qualitative agreement with the experimental results.

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FIGURE CAPTIONS

FIG. 1. (color) (a) Intensity of hard x rays with $h\nu > 40$ keV (black curve) compared with laser drive (red curve). (b) Time-resolved spectral measurement of $3\omega/2$ emission compared with laser drive (red curve) and spectrally integrated time history (black and white curve). (c) Time-resolved SRS with spectrally integrated time history (black and white curve) and laser drive (red curve).

FIG. 2. (color) Scaling of window hot electron (a) E_{hot} and (b) T_{hot} with the overlapped laser intensity of the cone 3 beams on the LEH window for $n_e = 0.04\ n_{cr}$ (red/black circles for drive A/B) and $n_e = 0.1\ n_{cr}$ (black triangles for drive A).

FIG. 3. (color) E_{hot} - T_{hot} plane with OMEGA window hot electron data scaled to a NIF ignition hohlraum for $n_e = 0.04\ n_{cr}$ (red/black circles for drive A/B) and $n_e = 0.1\ n_{cr}$ (black triangles for drive A). The blue dotted line indicates the NIF early time limit for hot electrons.